X-RAY EMISSION FROM CENTRAL BINARY SYSTEMS OF PLANETARY NEBULAE

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ABSTRACT

We study the conditions under which a main sequence binary companion to the central ionizing star of a planetary nebula (PN) might become magnetically active and thereby display strong X-ray luminosity, $L_x \gtrsim 5 \times 10^{29}$ erg s^{-1}. Since most PNe are older than few billion years, any main sequence companion will rotate too slowly to have magnetic activity and hence bright X-ray emission, unless it is spun-up. We demonstrate that if the orbital separation during the AGB phase of the PN progenitor is $a \lesssim 30 - 60$ AU, main sequence companions in the spectral type range F7 to M4 (mass range $0.3M_\odot \lesssim M_2 \lesssim 1.3M_\odot$) will accrete enough angular momentum from the AGB wind to rotate rapidly, become magnetically active, and exhibit X-ray luminosities $L_x \gtrsim 5 \times 10^{29}$ erg s^{-1}. Lower mass M stars and brown dwarfs can also become magnetically active, but they should have small orbital separations and hence are less likely to survive the AGB phase of the progenitor. For orbital separation of $a \lesssim 0.3$ AU, i.e., for a binary systems that went through a common envelope phase, the fast wind from the central WD star will interact with (and potentially disrupt) the companion's corona on the side facing the central star, while for $a \lesssim 6R_\odot$, i.e., an orbital period of $P_{\rm orb} \lesssim 30$ hours, the WD's fast wind will compress a dense small region near the surface of the companion. This region may thermally emit X-rays with nonnegligible luminosity. We estimate that $20 - 30\%$ of elliptical PNe and $30 - 50\%$ of bipolar PNe are likely to have magnetically active companions which will reveal themselves in X-ray observations. Re-analysis of Chandra X-ray Observatory spectroscopy of the compact central source of NGC 7293 indicates that the emitting region of this object possesses abundance anomalies similar to those of coronally active main-sequence stars. High-resolution X-ray spectroscopy of this and other compact sources in PNe are necessary to confirm a coronal origin for the X-ray emission.

Subject headings: planetary nebulae−stars: mass loss−stars: magnetic field−X-rays: stars

1. INTRODUCTION

Planetary nebulae (PNe) – the ejected, ionized envelopes of expired red giants – represent very late stages in the deaths of intermediate-mass (1-8 $M_{\odot}$) stars. Einstein and ROSAT observations revealed that many PNe are X-ray sources (see Kastner *et al.* 2000 and references therein). None of these nebulae was extended and/or bright enough in X-rays to be resolved spatially by the Einstein or ROSAT X-ray telescopes. However, a small fraction of the PN X-ray sources detected by ROSAT appeared too hard ($T_x > 10^6$ K) for the emission to be ascribed to a recently revealed, central white dwarf (e.g., Kreysing *et al.* 1992, Guerrero, Chu, & Gruendl 2000). Prior to the launch of the Chandra X-ray Observatory (CXO), this relatively high-temperature emission served as the best evidence for the presence of extended, shock-heated X-ray emission from PNe.

Recent observations by the *Chandra* X-Ray Observatory (Guerrero *et al.* 2001, hereafter GCGWK; Chu *et al.* 2001; Kastner *et al.* 2000; Kastner, Vrtilek & Soker 2001) have established, however, that PNe can in principle harbor two types of (relatively) bright, hard X-ray emitting regions: diffuse thermal emission from a large cavity inside the main nebular shell and a point-like region near the central star. In the present paper we consider the nature of these latter, point-like X-ray emission sources.

Chandra imaging of the PNe NGC 6543 (the Cat's Eye nebula) and NGC 7293 (the Helix nebula) reveal that each possesses a hard point source, with characteristic temperatures of $\sim 2 \times 10^6$ K and $\sim 7 \times 10^6$ K, and luminosities of $\sim 10^{30}$ erg s^{-1} and $\sim 3 \times 10^{29}$ erg s^{-1}, respectively (GCGWK). In addition the X-ray emission from the central source in NGC 7293 appears time variable (GCGWK). Point sources were not obviously detected in BD +30 3639 or NGC 7027, the only other PNs thus far imaged by Chandra (the compact source near the central star of NGC 7027 is most likely a knot of extended emission). GCGWK qualitatively discuss four mechanisms for the formation of the central point-like hard X-ray emission in NGC 6543 and NGC 7293:

1. Interaction of a fast ($\sim$ 1000 km s^{-1}) wind from the central star with the nebular gas. (Although the central ionizing star is evolving to become a WD, we term it here a WD). GCGWK rule out this possibility since presently NGC 7293 has no fast wind, and the interaction between the fast wind and the nebulae gas will form an extended source, as indeed is observed in NGC 6543 (Chu *et al.* 2001), BD+303639 (Kastner *et al.* 2000), and NGC 7027 (Kastner *et al.* 2001).

2. Shocks in the fast stellar wind, similar to a mechanism suggested to explain X-ray emission from massive O and B stars. GCGWK argue that such a process may occur in NGC 6543.

3. Accretion of material from a close binary companion by the ionizing WD star. GCGWK rule this out as it is inconsistent with both the X-ray temperature and the lack of optical time variability.

4. Coronal (magnetic) activity of a main sequence binary companion. A dwarf (main sequence)

M companion will not be detected due to its low bolometric luminosity, but it may be magnetically active enough to emit the observed X-ray luminosity. The time variability of NGC 7293 (GCGWK) and of NGC 6543 in Hα (Gruendl *et al.* 2001) support the hypothesis of a dMe (dwarf M star with strong emission) companion with magnetic activity.

In the present paper we conduct a theoretical study of two mechanisms by which a main sequence companion to the WD ionizing source of the PN can lead to X-ray emission: magnetic activity of a companion (process 4 studied by GCGWK), and the collision of the fast wind from the WD with the corona of a main sequence companion. The former magnetic activity mechanism is not to be confused with the X-ray point source emission mechanism from the central WD proposed by Blackman, Frank, & Welch (2001). We explore the implications of binary interaction since, as we discuss in §2, it is exceedingly likely that a large fraction of PNe possess close binary central stars. In §2 we study both the companion magnetic activity and WD-companion interaction processes. The implications for observations are discussed in §3, while a short summary is presented in §4.

2. X-RAY EMISSION FROM BINARY CENTRAL SYSTEMS

2.1. Magnetic Activity on a Late Type Companion

2.1.1. Requirements for luminous X-ray emission

The magnetic activity (e.g., Saar & Brandenburg 1999) and the X-ray luminosity (e.g., Neuhäuser *et al.* 1995) of main sequence stars type F7 to M decreases with increasing age or orbital rotational period. Stars earlier than F7 have very weak magnetic activity (e.g., Saar & Brandenburg 1999). As described later, most surviving active companions to PN central stars have masses in the range $0.3M_\odot \lesssim M_2 \lesssim 1.3M_\odot$, spectral type K4−F7. A steep decrease in activity seems to occur at an age of $\sim 10^9$ yr, when the X-ray luminosity falls below 10^{29} erg s^{-1}, much below the luminosities found by GCGWK in the central sources of NGC 6543 and NGC 7293. To be active, either the companion to the central ionizing star (the WD) is a very young star, age $\lesssim 3 \times 10^8$ yr, or else it has been spun-up by accretion and/or tidal interaction. A young companion means fast evolution of the PN progenitor, which implies a massive progenitor, i.e., $M_i \gtrsim 3M_\odot$, hence probably a bipolar PN. Not many PNe belong to this group; most elliptical PNe are formed from stars having initial mass of $1M_\odot \lesssim M_i \lesssim 2M_\odot$, hence any main sequence companion of type G to M will be a slowly rotating star with low magnetic activity, i.e. $L_x \lesssim 3 \times 10^{28}$ erg s^{-1}. We therefore study the possibility that the companion is spun-up by accretion.

We first estimate the rotation period (or velocity) needed to achieve high activity, on the level of $L_x \gtrsim 5 \times 10^{29}$ erg s^{-1}. We crudely fit the data on the Pleiades, Hyades and the sun given by Neuhäuser *et al.* (1995) and Stelzer & Neuhäuser (2001) by

$$L_x \simeq 10^{29}[3.40 - 2.37 \log(P/\text{ day})] \text{ erg s}^{-1} \qquad \text{P} < 26 \text{ day}, \tag{1}$$

where $P = 2\pi/\Omega$ is the rotational period and Ω the angular velocity. For long orbital periods we derive a relation based on optical observations of active stars. From Brandenburg, Saar & Turpin (1998) we take the relation between the Ca H and K flux divided by the bolometric luminosity, $\langle R'_{\rm HK}\rangle$, and the magnetic field, i.e., $\langle R'_{\rm HK}\rangle \propto (\langle B\rangle / B_{\rm eq})^{0.47}$, where $\langle B\rangle$ is the average magnetic field and $B_{\rm eq}$ is the equipartition (with gas pressure) magnetic field value. From Saar & Brandenburg (1999) we take the relation between $\langle R'_{\rm HK}\rangle$ and the Rossby number Ro$\equiv (2\Omega\tau_c)^{-1}$, that is, $\langle R'_{\rm HK}\rangle \propto Ro^{-1}$, where τ_c is the convective overturn time, and the Rossby number is basically the ratio between the rotation period and the convective overturn time. Neglecting differences in $B_{\rm eq}$ and τ_c between different types of stars (F7 to M4) we find that $\langle B\rangle \propto {\rm Ro}^{-2}$. Collier, Cameron & Li (1994), who study magnetic braking, argue for $\langle B\rangle \propto {\rm Ro}^{-1}$. For the purposes of the present study we use the results of Saar & Brandenburg (1999), which are based on magnetic activity. Assuming that the X-ray luminosity is proportional to the magnetic energy density $L_x = \langle B\rangle^2$ we obtain the following relation

$$L_x \simeq 2.3 \times 10^{29} \left(\frac{P}{10 \text{ day}}\right)^{-4} \text{ erg s}^{-1} \qquad \text{P} \gtrsim 7 \text{ day}, \tag{2}$$

where the scaling was chosen to fit the sun, $P = 26$ day and $L_x = 5 \times 10^{27}$ erg s^{-1}. Equation (1) and (2) become equal for $P = 13.3$ day, while the derivative dL_x/dP of equations (1) and (2) becomes equal for $P = 14$ day, hence we take equation (1) for $P < 13$ day and equation (2) for $P \geq 13$ day. The X-ray luminosity from ROSAT observations of K stars (Wheatley 1998) and of the open cluster IC 4665 (Giampapa, Prosser & Fleming 1998) can be fitted with the same form as equation (1), but with a higher maximum activity and a steeper rise with angular velocity

$$L_x \simeq 10^{30}[1 - \log(P/\text{ day})] \text{ erg s}^{-1},, \tag{3}$$

for K stars with periods in the range $0.4 < P < 9.8$ day.

The relevant conclusion from equations (1)-(3) and the papers cited in relation to these equations is that, to reach an X-ray luminosity of $L_x > 5 \times 10^{29}$ erg s^{-1}, a main sequence companion of spectral type F7 to M4 has to be spun up to $P \lesssim 3$ day. For a solar type star the equatorial rotation velocity should be $v_{\rm rot} \gtrsim 20$ km s^{-1}, or about an order of magnitude faster rotation than the present sun has. We take this as the condition on the rotational velocity and period to induce magnetic activity in companions of PN central stars.

2.1.2. Accretion by the companion star

The mass accretion rate is taken to follow the Bondi-Hoyle relation $\dot{M}_a = \pi R_a^2 v_r \rho$, where $R_a = 2GM_2/v_r^2$ is the accretion radius, and v_r is the relative velocity between the wind and the companion. The density is that of the primary wind $\rho = \dot{M}_1/(4\pi a^2 v_{w1})$, where $\dot{M}_1$ is the mass loss rate (taken to be positive), a is the orbital separation, and v_{w1} the primary wind velocity. For accretion from a wind, the net specific angular momentum of the material entering the Bondi-Hoyle accretion cylinder with radius R_a, i.e., the material having impact parameter $b < R_a$, is

$j_{BH} = 0.5(2\pi/P_o)R_a^2$ (Wang 1981), where P_o is the orbital period. Livio *et al.* (1986; see also Ruffert 1999) find that the actual accreted specific angular momentum for high Mach number flows is $j_a = \eta j_{BH}$, where $\eta \sim 0.1$ and $\eta \sim 0.3$ for isothermal and adiabatic flows, respectively. The relative velocity is $v_r^2 \simeq v_{w1}^2 + v_o^2$, where v_{w1} is the (slow) wind velocity at the location of the accreting star, and v_o is the relative orbital velocities of the two stars. We find below that the orbital separation above which no spin-up occurs is > 10 AU; at this separation, the orbital velocity is lower than the wind speed. We therefore take $v_r \simeq v_{w1} \simeq 15$ km s^{-1} in what follows. If an accretion disk is formed, then the specific angular momentum of the accreted mass is that at the inner boundary of the disk, i.e., the specific angular momentum of a particle in a Keplerian orbit at the equator of the accreting star of radius R_2 and mass M_2, $j_2 = (GM_2R_2)^{1/2}$. An accretion disk will be formed if $j_a > j_2$. Substituting typical values for main sequence accretor and the mass-losing terminal AGB star, e.g., a mass of $0.6M_\odot$ at the end of the AGB, we find the following condition for the formation of a disk

$$1 < \frac{j_a}{j_2} \simeq 1.3\left(\frac{\eta}{0.2}\right)\left(\frac{M_1+M_2}{1.6M_\odot}\right)^{1/2}\left(\frac{M_2}{1M_\odot}\right)^{3/2}\left(\frac{R_2}{1R_\odot}\right)^{-1/2}\left(\frac{a}{20\text{ AU}}\right)^{-3/2}\left(\frac{v_r}{15\text{ km s}^{-1}}\right)^{-4}, \quad (4)$$

where the expression is for a circular orbit with semi-major axis a. The mass accretion rate decreases strongly with increasing wind speed, hence most of the mass will be accreted during the AGB phase, when the wind speed is low. If the AGB star loses a mass of $\Delta M_{\rm AGB}$, the total accreted mass by the companion is

$$\Delta M_{\rm acc} \simeq 0.04\Delta M_{\rm AGB}\left(\frac{M_2}{1M_\odot}\right)^2\left(\frac{a}{20\text{ AU}}\right)^{-2}\left(\frac{v_r}{15\text{ km s}^{-1}}\right)^{-4}. \quad (5)$$

The moment of inertia of a companion F7−M4 spectral type star is $I \simeq 0.1M_2R_2^2$, and the rotation velocity is $v_{\rm rot} = J_aR_2/I$, where J_a is the accreted angular momentum. Here we assume solid body rotation, which is a reasonable assumption for these stars, which have convective envelopes. We first consider accretion from an accretion disk, whose formation is described by equation (4) for systems having an orbital separation of $a \lesssim 20$ AU, or even $a \lesssim 60$ AU for a slow wind, $v_{w1} \simeq 10$ km s^{-1}, at the final stages of the AGB (Soker 2001). Note that the relevant orbital separation is that characterizing the accretion phase, and not the initial separation; for systems with $a > 20$ AU the final separation will be larger than the initial one due to mass loss. We find for accretion from a disk

$$v_{\rm rot} \simeq 90\left(\frac{\Delta M_{\rm AGB}}{0.5M_\odot}\right)\left(\frac{M_2}{1M_\odot}\right)^{3/2}\left(\frac{R_2}{1R_\odot}\right)^{-1/2}\left(\frac{a}{20\text{ AU}}\right)^{-2}\left(\frac{v_r}{15\text{ km s}^{-1}}\right)^{-4}\text{ km s}^{-1}. \quad (6)$$

In case a disk is not formed, and the material is accreted directly onto the star, the accreted angular momentum is $J_a = \Delta M_{\rm acc} j_a$. Using the expressions for j_a and $\Delta M_{\rm acc}$ given above we find for accretion directly onto the star

$$v_{\rm rot} \simeq 110\left(\frac{\Delta M_{\rm AGB}}{0.5M_\odot}\right)\left(\frac{M_2}{1M_\odot}\right)^3\left(\frac{R_2}{1R_\odot}\right)^{-1}\left(\frac{M_1+M_2}{1.6M_\odot}\right)^{1/2}\left(\frac{a}{20\text{ AU}}\right)^{-7/2}\left(\frac{v_r}{15\text{ km s}^{-1}}\right)^{-8}\left(\frac{\eta}{0.2}\right)\text{ km s}^{-1}. \quad (7)$$

Both equations (6) and (7) show that F7−M4 spectral type main sequence stars in the mass range $0.3 \lesssim M_2 \lesssim 1.3 M_\odot$ that are accreting from an AGB wind will be spun-up sufficiently to have strong magnetic activity if the orbital separation is $a \lesssim 30$ AU (with smaller orbital separations for lower mass stars) for $v_{w1} \simeq 15$ km s^{-1}. The range of separations may be larger ($a \lesssim 65$ AU) if, during the final intensive wind phase of the AGB, the wind velocity is lower, i.e., $v_{w1} \simeq 10$ km s^{-1} (the total mass lost would then be only $\Delta M_{\rm AGB} \sim 0.2 M_\odot$; Soker 2001). Such companions are likely to substantially shape the PN, such that it becomes an extreme elliptical or even bipolar nebula (Soker 2001).

For much smaller orbital separations, $a \lesssim 2$ AU, the companion accretes via Roche lobe overflow and/or enters the primary's envelope. In both cases it will be spun-up substantially. Hence, we predict that all close binary systems in PNe should show magnetic activity if the companions are within the approximate spectral type range F7 through M, and even brown dwarfs if survive the evolution. Finally, note that we do not consider the variation of accretion rate along eccentric orbits, but rather consider only the semi-major axis a; the uncertainties in other parameters (e.g., the exact dependence of X-ray luminosity on rotation rate) preclude such a treatment.

Low mass main sequence and brown dwarf companions will also be spun-up via mass accretion during the central star's AGB phase. However, they need to be at orbital separations of $a \lesssim 10$ AU in order to accrete enough angular momentum to become magnetically active and thereby display bright X-ray emission. Many of these objects would not survive to the PN phase since they would enter the AGB envelope by tidal interaction, and then spiral all the way in and collide with the AGB core. This is the reason for taking the lower companion mass to be $\sim 0.3 M_\odot$, although some lower mass companions may survive if they are not too close to the envelope, but still close enough to accrete enough angular momentum. We estimate the initial orbital range for $\sim 0.1 - 0.3 M_\odot$ companions for both surviving and being spun-up to strong magnetic activity to be $5 \lesssim a_i \lesssim 10$ AU, or up to ~ 20 AU if the primary terminates the AGB with a relatively slow wind ($v_{w1} \simeq 10$ km s^{-1}).

2.2. Colliding White Dwarf and Companion Winds

In the sun the X-ray luminosity $L_{x,\odot}$ is of the same order of magnitude as the rate of kinetic energy carried by the solar wind $\dot{E}_k$, $L_{x,\odot} \simeq \dot{E}_k \simeq 3 \times 10^{27}$ erg s^{-1}. Collier Cameron & Li (1994) argue that the mass loss rate from main sequence stars scales either linearly or as square of the surface magnetic field. Based on the behavior of the Sun, we take $\dot{E}_k = L_x$. By analogy, the mass loss rate of a main-sequence companion to a PN central star (defined positively) is then

$$\dot{M}_2 \simeq 10^{-11} \left(\frac{L_x}{10^{30} \text{ erg s}^{-1}} \right) M_\odot \text{ yr}^{-1}. \tag{8}$$

During the early PN phase the central ionizing source — the emerging WD — blows a fast wind, which will collide with the main sequence companion's wind. The stagnation point is where the ram pressures of the two winds are equal, i.e., $\rho_f v_f^2 = \rho_2 v_2^2$, where subscripts f and 2 stand for

the fast wind from the primary and the wind from the secondary main sequence star, respectively. Substituting for the density and scaling with typical values we obtain

$$d_2 \simeq 0.016a \left(\frac{L_x}{10^{30} \text{ erg s}^{-1}}\right)^{1/2} \left(\frac{\dot{M}_f v_f}{2 \times 10^{-5} M_\odot \text{ yr}^{-1} \text{ km s}^{-1}}\right)^{-1/2} \left(\frac{v_2}{500 \text{ km s}^{-1}}\right)^{1/2}, \tag{9}$$

where d_2 is the distance of the stagnation point from the companion's center. The electron density n_{2e} of the companion's shocked wind at the stagnation point is four times the free wind density,

$$n_{2e} \simeq 9 \times 10^4 \left(\frac{a}{20 \text{ AU}}\right)^{-2} \left(\frac{\dot{M}_f v_f}{2 \times 10^{-5} M_\odot \text{ yr}^{-1} \text{ km s}^{-1}}\right) \left(\frac{v_2}{500 \text{ km s}^{-1}}\right)^{-2} \text{ cm}^{-3}. \tag{10}$$

The shocked secondary wind gas temperature is $T \simeq 3.5 \times 10^6$ K, and its cooling time is

$$\tau_c \simeq 20 \left(\frac{a}{20 \text{ AU}}\right)^2 \text{ yr}. \tag{11}$$

The flow time of the shocked gas out from the interaction region is $\tau_f \sim d_2/v_2$ for $d_2 \gtrsim R_2$, and $\tau_f \sim R_2/v_2$ for $d_2 \lesssim R_2$. For $R_2 = R_\odot$, the mass loss rate from the secondary as determined from equation (8), and a WD wind of $\dot{M}_f v_f = 2 \times 10^{-5} M_\odot$ yr^{-1} km s^{-1}, we find $d_2 = R_2$ for $a \simeq 0.3$ AU. For $d_2 \gtrsim R_2 \simeq R_\odot$ the flow time is much shorter than the cooling time, hence the shocked secondary wind will radiate only a tiny fraction of its thermal energy before flowing away from the wind interaction region and expanding, hence increasing farther its cooling time. In that case the thermal X-ray emission from the shocked secondary wind is negligible.

We next examine the situation when the two stars are very close, and the WD wind compresses the corona of the main sequence companion. The density is determined by the ram pressure of the WD fast wind, hence it is still given by equation (10) and the cooling time is given by equation (11). The flow time is $\tau_f \sim R_2/v_2 \simeq 20$ minutes. The flow time will be longer than the cooling time for $a \lesssim 6R_\odot$, which corresponds to an orbital period of $P_{\rm orb} \lesssim 30$ hours. The condition for significant X-ray emission from the thermalized outflow from the companion is therefore

$$a \lesssim 6 \left(\frac{\dot{M}_f v_f}{2 \times 10^{-5} M_\odot \text{ yr}^{-1} \text{ km s}^{-1}}\right)^{1/2} R_\odot. \tag{12}$$

We note the following properties of this compression process.
(1) The WD wind compresses its main sequence companion's corona on the side facing the WD, to a very thin "shell". This is true already for $a \lesssim 0.3AU = 65R_\odot$ ($P_{\rm orb} \lesssim 0.13$ yr), as noted above. In this case we expect the magnetic activity (and therefore flaring) on the side of the companion facing the WD to be disrupted. It is uncertain as to whether the companion's X-ray luminosity would decrease or increase given such conditions.
(2) For $a \lesssim 6R_\odot$ the electron density in the compressed corona on the side facing the WD reaches values of $n_{2e} \gtrsim 5 \times 10^{10}$ cm^{-3}. In this case the cooling time is shorter than the flow time, and the gas manages to emit most of its thermal energy. At these densities, collisional de-excitation

starts to be important, influencing the X-ray spectra. We stress, however, that the processes in close binary stars are much more complicated (e.g., Stepien, Schmitt, & Voges 2001) and a full treatment is beyond the scope of this paper.
(3) The volume occupied by the dense gas is very small. To achieve an X-ray luminosity of $L_x(\mathrm{wind}) = 5 \times 10^{29}$ erg s^{-1} on the side facing the WD, the shell thickness should be only $h_{\mathrm{shell}} \simeq 0.003(a/6R_\odot)^4 R_\odot$, for the fast wind parameters assumed above. This implies that the coronal structure will be totally disrupted by the WD winds, and that gasdynamical calculations are required before our simple estimates of the X-ray emission from the thermalized gas can be fully trusted.

3. OBSERVATIONAL IMPLICATIONS

3.1. The Fraction of PNe with Magnetically Active Binary Systems

In this subsection we estimate the fraction of PNe that we expect to possess a central binary system where the companion show magnetic activity. Due to the many uncertainties, e.g., the AGB wind velocity at the final intensive wind phase (Soker 2001), the exact condition to set magnetic activity in old stars, and the percentage of PNe formed from binary systems, our estimates are crude, but still may be meaningful for future observations.

Soker & Rappaport (2000) estimate that $\sim$ 10% of all PNe have tidal-strongly interacting binaries in which the secondary stays outside the AGB envelope most of the evolutionary time. Most of these systems form bipolar PNe. Most such binaries contain a main sequence companion, with half of spectral type F7$-$M4; such binaries therefore constitute $\sim$ 4% of all PNe. Another few percent of bipolar PNe are formed by common envelope evolution. Hence, in total, $\sim$ 15% of all PNe are bipolar, and in $\sim 5-8$% of these cases (i.e., $30-50$% of all bipolar PNe) we expect a magnetically active main sequence companion to be present.

From a population synthesis study, Soker (2001) found that $5-20$% of all PNe possess binary central stars wherein the companions accrete from the AGB wind and form an accretion disk, although the tidal interaction stays weak along the entire evolution (the lower value is for a fast AGB wind while the higher one is for a slow AGB wind). In half of these systems the companion is a WD, while in half (i.e., $\sim$ 7% of all PNe) the companion is a main sequence star. Hence, we estimate that $\sim$ 5% of all PNe central stars possess a companion that is an F7$-$M4 main sequence star which has been spun-up to be X-ray active via wind accretion. These are mainly elliptical PNe, in which the tidal interaction (between the companion and AGB star) is weak. From the population synthesis studies of Yungelson, Tutukov, & Livio, (1993), Han, Podsiadlowski, & Eggleton (1995), and Soker & Rappaport (2000), we estimate that another $\sim 20-25$% of all PNe formed via a common envelope interaction and form elliptical PNe. Most of these have a companion in the F7$-$M4 mass range that we have determined here to be X-ray emission candidates. However,

many of the central binaries in these PNe suffer mergers, such that the companion no longer exists. Bond & Livio (1990) and Bond (2000) estimate that $\sim 10-15\%$ of all PNe have close binary systems in their center. Based on these we estimate a contribution of $\sim 10-15\%$ of all PNe from these systems to the population of PNe with magnetically active main sequence stars. Overall, therefore, we estimate that $\sim 15-20\%$ of all PNe ($\sim 20-30\%$ of elliptical PNe) are elliptical and have magnetically active main sequence companions.

From the theoretical study by Yungelson *et al.* (1993) and observations of close binary systems in PNe (Bond & Livio 1990; Bond 2000) we estimate that for $\sim 5-10\%$ of all PNe, most (but not all) of which are elliptical, the orbital separation is $6R_{\odot} \lesssim a \lesssim 65R_{\odot}$. Hence the magnetic activity on the side of the companion facing the WD is disrupted, if the latter still blows a fast wind. However, many of these WDs would be in a phase where the fast wind has diminished and no longer influences the companion's magnetic activity. In another $\sim 5-10\%$ of all PNe, most of which are elliptical, the orbital separation is $a \lesssim 6R_{\odot}$, and we expect significant X-ray emission from the compressed corona, in the subset for which the central WD still has a fast wind (i.e., $\sim 3-7\%$ of all PNe).

3.2. X-ray Spectra

If the X-ray emission from compact sources at the cores of PNe is due to coronal activity, then we expect this emission to resemble spectroscopically that of stellar coronae. Such emission is characterized by an optically thin, line-dominated spectrum at temperatures of $\sim 10^7$ K; typical electron densities lie in the range $\log n_e \sim 9-12$, and abundance anomalies are commonplace (Linsky 2001). The high temperature alone is sufficient to distinguish such coronal emission from the emission due to a hot white dwarf at a PN's core (Guerrero *et al.* 2000; GCGWK).

Existing medium-resolution (CCD) X-ray spectra may provide some clues to the origin of the emission from PN cores. Here we present a re-analysis of one such dataset, for the central source of NGC 7293, obtained with the Chandra Advanced CCD Imaging Spectrometer (ACIS). These data (Observation ID 631) were first obtained and analyzed by GCGWK. Subsequent to publication of this analysis, the Chandra X-ray Center (CXC) released improved spectral calibration files for ACIS CCD S3 (Edgar 2001), with which the NGC 7293 data were obtained, prompting our re-analysis. We used standard data processing tools available as part of the CXC CIAO [1] package (version 2.1) to reprocess the Level 1 X-ray events and produce recalibrated Level 2 events. We then extracted the spectrum of the central source from the recalibrated Level 2 events, and constructed corresponding spectral response files. The source and spectral response file extraction region was defined as a $2''$ radius circle centered on the core point source of NGC 7293; a background spectrum was extracted from an annulus extending between $2''$ and $6''$ radius, and subtracted from the source

[1] http://asc.harvard.edu/ciao/

spectrum.

The resulting spectrum of the NGC 7293 point source is displayed in Figure 1 (1a for solar abundances, and 1b for non-solar abundances). Note that, with re-calibration, the spectrum is revealed to be somewhat harder than indicated in Fig. 2 of GCGWK, peaking between 0.8 and 1.0 keV (rather than between 0.7 and 0.85 keV). This suggests that Ne emission is anomalously bright in the NGC 7293 spectrum. Hence, we attempted spectral fitting with the MEKAL plasma model (Mewe, Lemen, & van den Oord 1986) using both solar abundances and non-solar abundances, where in the latter case we varied the abundances of Ne and other elements (Fe, Mg, O) with prominent emission lines that fall within the energy range of bright emission from NGC 7293.

Results of this fitting exercise are illustrated in Fig. 1. In the cases of both solar and non-solar abundances, the best-fit temperature is found to be $kT_x \sim 0.7$ keV for an assumed column density of $N_H = 4 \times 10^{20}$ cm $^{-2}$, the value determined by GCGWK (we find that the fits are not sensitive to the value of N_H). It can be seen, however, that a model holding abundances at solar produces a fit slightly inferior to that of the non-solar abundance model. In the latter model, we find best-fit abundances for O, Ne, Fe, and Mg of 0.1, 1.2, 0.3, and 0.3 relative to solar (with formal uncertainties of $\pm 20\%$). Note that neither model is able to account for the apparent excess emission at ~ 1.1 keV, which may be due to anomalously bright Fe L emission (our attempts to increase the Fe abundance to account for this emission result in a large overestimate of the emission intensity at ~ 0.9 keV).

The abundances determined in the above fitting exercise are similar to those characteristic of the so-called "inverse first ionization potential effect" that is commonly observed in stellar coronae (e.g., Drake *et al.* 2001). Hence these results would appear to support a coronal origin for the X-ray emission from NGC 7293. However, we caution that the X-ray spectra of extended nebular emission also display prominent line emission and are characterized by abundance anomalies (Chu *et al.* 2000; Kastner *et al.* 2000, 2001). Thus, the presence of such anomalies is not sufficient, in and of itself, to conclude that compact X-ray sources within PNe are coronal in nature. High-resolution spectroscopy — such as that enabled by the Chandra X-ray Observatory High Energy Transmission Gratings and the X-ray Multiple Mirror Reflection Gratings Spectrometer — is needed, to determine more precise abundances as well as electron densities. The latter may represent the most conclusive available test of the coronal model (Kastner *et al.* 2002).

4. SUMMARY

GCGWK argue that the unresolved hard X-ray emission from the center of the PN NGC 7293 comes from a dMe magnetically active companion, and that a similar source may explain the hard X-ray emission from the center of the PN NGC 6543. Motivated by these findings — and by the common view that stellar companions shape many PNe and that many of these companions will be on the main sequence — we study the conditions for X-ray emission from magnetically active,

spun-up main sequence (and even brown dwarf) stellar companions to central stars of planetary nebulae (PNe). Our main results can be summarized as follows.

(1) We estimate that companions of spectral type F7−M4 must have an equatorial rotational velocity of $\gtrsim 20$ km s^{-1} in order to have sufficient magnetic activity to generate X-ray luminosities on the order of those observed for the point sources within PNe, i.e., $L_x \gtrsim 5 \times 10^{29}$ erg s^{-1}. Since most PNe are older than a few billion years, any main sequence companion will rotate much more slowly than this; therefore, we conclude that X-ray emitting, main-sequence companions have been spun up, most likely via accretion of mass from the former AGB star that generated the PN. We concentrated on companions in this spectral type range (F7−M4) because companions earlier than F7 will not show magnetic activity, while low mass stars later than M4 need to be close to the AGB progenitor in order to accrete enough mass from the wind to be spun-up. Such very low mass companions are likely to enter the envelope of the AGB star (i.e., they will undergo a common envelope phase) and are therefore unlikely to survive.

(2) We found that main sequence companion stars will be spun up (by acquiring angular momentum from the AGB progenitor's wind) if the orbital separation during the AGB phase is $a \lesssim 30$ AU (orbital period of $P_{\rm orb} \lesssim 130$ yrs for a binary combined mass of $1.6 M_\odot$) and a wind speed of ~ 15 km s^{-1}. For a slower AGB wind of ~ 10 km s^{-1}, the condition is $a \lesssim 65$ AU (orbital period of $P_{\rm orb} \lesssim 400$ yrs). Late K to M stars, and even brown dwarfs, need to have somewhat smaller orbital separations to be spun-up and thereby become magnetically active. Much closer companions will be spun-up via accretion from a Roche lobe overflow or by common envelope evolution. Binary systems that go through a common envelope phase end with much closer orbital separations.

(3) If the final orbital separation is $a \lesssim 65 R_\odot$ ($P_{\rm orb} \lesssim 0.13$ yr) then the fast wind from the central ionizing source (the eventual WD), if still active, is likely to influence the magnetic activity of the companion on the side facing the ionizing source. It is not clear if this will increase or decrease the X-ray emission.

(4) If the final orbital separation is $a \lesssim 6 R_\odot$ ($P_{\rm orb} \lesssim 30$ hours) the fast wind from the central WD star will compress a very dense region close to the companion side facing the WD.

(5) We crudely estimated that $20 - 30\%$ of elliptical PNe and $30 - 50\%$ of bipolar PN are likely to have magnetically active companions which will reveal themselves in X-ray observations. If we take bipolar and elliptical PNe to be $\sim 15\%$ and $\sim 75\%$ of all PNe, respectively, we find that $20 - 30\%$ of all PNe are expected to harbor magnetically active, and therefore X-ray luminous, main sequence companions.

(6) We reanalyzed Chandra X-ray Observatory spectroscopy of the compact central source of NGC 7293 (previously studied by GCGWK). This modeling, while inconclusive, suggests that the emitting region of this object possesses abundance anomalies similar to those of coronally active main-sequence stars, with Ne somewhat overabundant and Fe underabundant relative to solar.

High-resolution X-ray spectroscopy of this and other compact sources in PNe are necessary to confirm a coronal origin for the X-ray emission.

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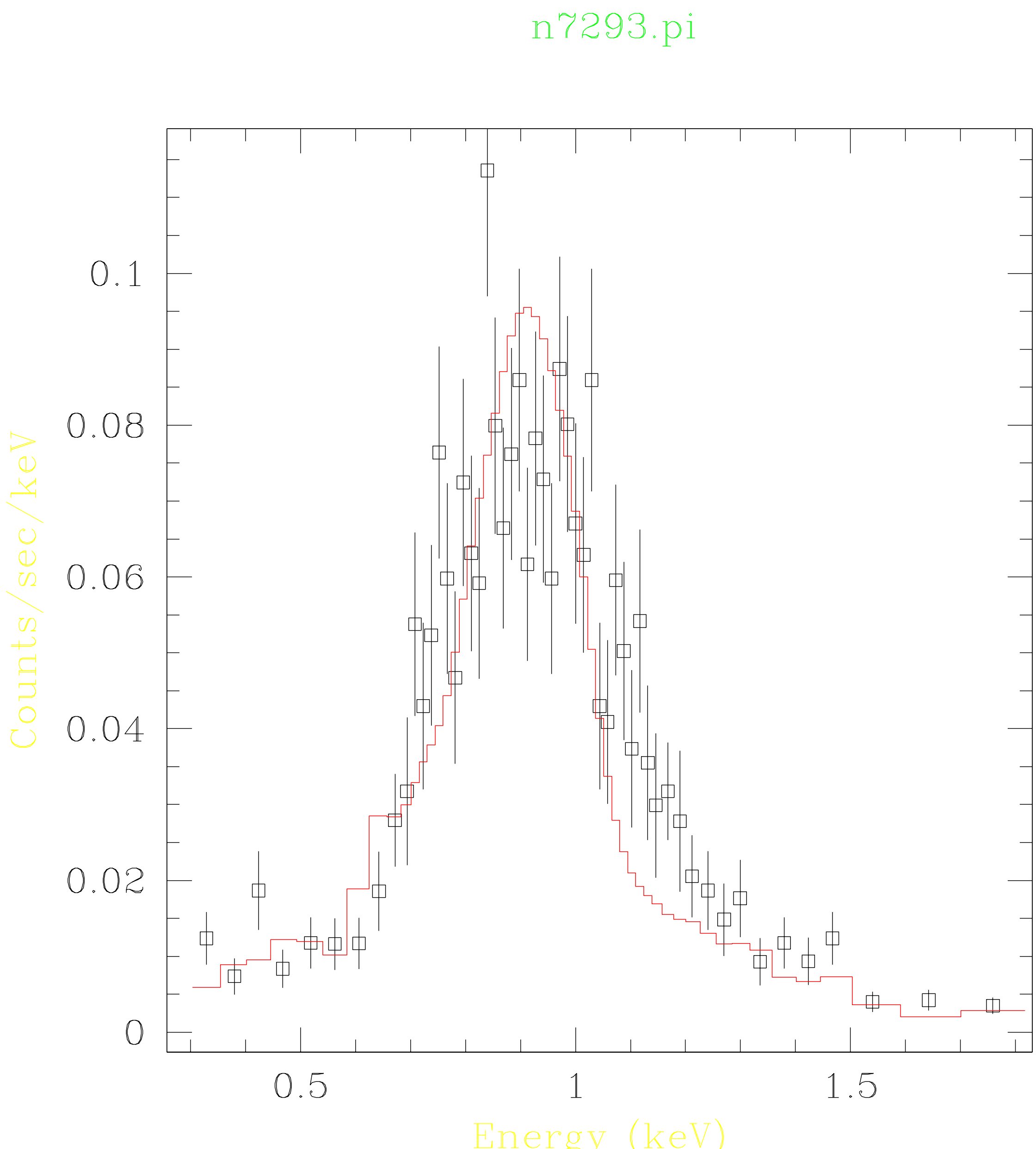

Fig. 1a.— Chandra/ACIS spectrum of the central compact source of NGC 7293, overlaid with the results of fitting MEKAL models with solar abundances (a), and non-solar abundances (b). In the latter model, emission from Ne is enhanced, while emission from O, Mg, and Fe is somewhat suppressed.

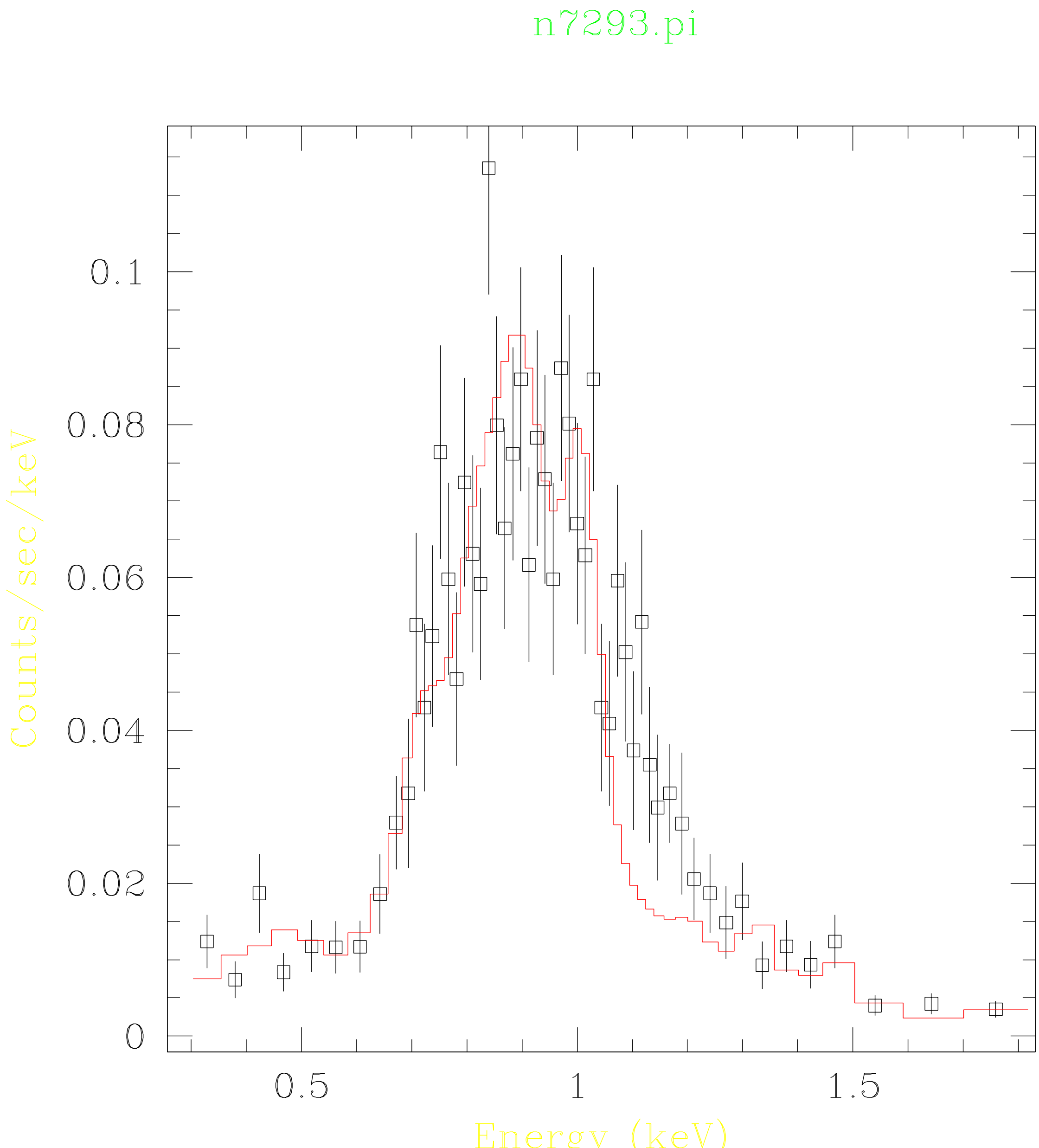

Fig. 1b.—